TESTBED VERIFICATION OF PATHFINDER'S MARTIAN ENTRY, DESCENT, AND LANDING (EDL)

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ABSTRACT

Mars Pathfinder is the second spacecraft to be developed as a NASA Discovery mission. Pathfinder employed unique innovations throughout the entire spacecraft that allowed mission development to be accomplished within the 3 year design schedule and $150 million (FY '92 dollars) cost constraint imposed under the Discovery classification.

Pathfinder's greatest innovation is it's low cost approach of getting a lander to the Martian surface. In the entry, descent, and landing (EDL) phase of the mission, flight software uses data collected by on-board accelerometers and a radar altimeter to accurately jettison hardware, deploy a parachute, fire rocket deceleration motors, inflate airbags, and open the lander. While several test facilities across the country validated the individual mechanical components of EDL, all of the system level acceptance testing was per-formed at the Jet Propulsion Laboratory (JPL) in the Flight System Testbed for Mars Pathfinder (FST/P). Flight hardware was directly stimulated by test equipment to produce data measurements similar to the expected Martian descent and landing profiles. Flight software's response to these data inputs was analyzed to verify the proper performance of the entire system throughout the EDL phase.

Pathfinder successfully reached Mars on July 4, 1997. Prior to this historical event, a tremendous amount of time was invested in the verification of the flight code that would perform EDL. Testing continued long after Pathfinder was launched in order to complete outstanding test cases and examine several potential problem areas. The result of this effort was the uplinking of a new version of code a month before reaching Mars. The effort proved worthwhile as signals sent from the surface of Mars initially indicated the successful completion of EDL, and later revealed the incredible landscape of Pathfinders new home.

MARS PATHFINDER OVERVIEW

The Pathfinder mission to Mars marks Americas return to the Martian surface after 21 years. Making extensive use of technology and hardware developed for other interplanetary missions, Pathfinder accomplished it's development as a NASA Discovery mission. Under this classification, the development phase was limited to 3 years with a fixed cost of $171 M real year dollars ($ 150M in FY 1992 dollars). In the end, Pathfinder not only validated NASA's "faster, better, cheaper" way of doing business, it established a new and robust method of getting to the Martian surface.

Developed, built, and operated by the Jet Propulsion Laboratory in Pasadena, California, Mars Pathfinder was launched on December 4, 1996 aboard a McDonnell Douglas Delta 11 launch vehicle from the Air Force station in Cape Canaveral, Florida. A Payload Assist Module (PAM-D) upper stage sent Pathfinder out of Earth's orbit and on to Mars. Following a seven month cruise, Pathfinder safely arrived on the Martian surface on July 4, 1997.

Mars Pathfinder can be thought of as three individual spacecraft (figure l); the cruise. entry, and landed vehicles. The main component of the cruise vehicle is the cruise stage. Responsible for gathering attitude data and performing trajectory correction maneuvers during the seven month cruise phase of the mission, the cruise stage is jettisoned prior to entry into the Martian atmosphere. With the loss of this hardware. Pathfinder's shape becomes more like that of a typical entry vehicle. The heatshield and backshell protected the lander from the intense heat generated while passing through the atmosphere. The heatshield then dropped away, and the backshell housed the parachute and retro rockets that further slowed the lander's descent Finally, the Pathfinder lander not only contains the airbags and petal motors that cushioned it's impact with the red planet and subsequently righted itself, it also houses the sole processor and all critical power and telecom hardware.

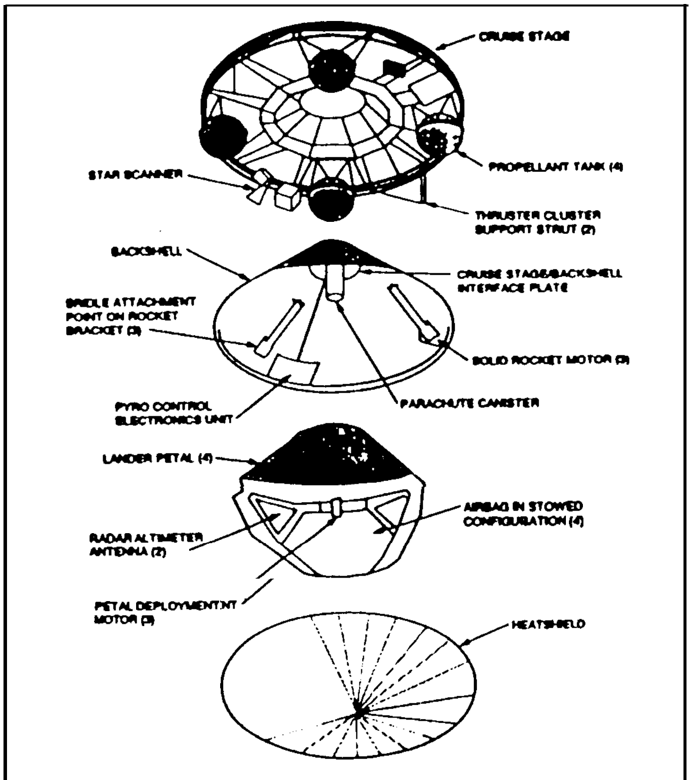

Figure 1. Mars Pathfinder Flight System

While the main objective of the Pathfinder mission was to develop a low cost delivery system to the Martian surface and return data gathered during the Martian descent, perhaps the most exciting part of the spacecraft was it's stowaway. Pathfinder delivered the Sojourner rover to the surface, and on the evening of their second day on Mars, the rover rolled down Pathfinder's ramps and became the first remote vehicle to set wheel on the Martian surface. Able to move around the landing site and perform numerous experiments, Sojourner also carried the Alpha, Proton, X-ray Spectrometer (AXPS) experiment that would allow scientists to determine the elemental compositions of various rocks. In addition to the rover, the Pathfinder lander carried 2 science experiments of it's own. The Imager for Mars Pathfinder (IMP) provides stereoscopic imaging of the landing site in addition to gathering spectral composition data by looking at the surroundings through one of 12 separate filters. The Atmospheric Science Instrument / Meteorology (ASI/MET) can collect pressure. temperature. and wind measurements on the surface after gathering acceleration. temperature and pressure data during Pathfinders descent to the Martian surface.

Located about 1000 km from the Viking i landing site, the Pathfinder mission touched down in the ancient outflow channel named Ares Valles. This site was scientifically attractive due to the possibility that a wide variety of rocks might have been deposited in the channel by a massive water flow that once raced through this area. The selected landing site has lived up to ail expectations resulting in spectacular images, interesting rock samples, and challenging terrain to verify the rover's usefulness in future planetary exploration.

ENTRY, DESCENT, AND LANDING (EDL) OVERVIEW

In order to meet the development schedule and cost cap, Pathfinder devised a new approach to get to the surface of Mars. Unlike the Viking missions of the early 1970's which orbited Mars prior to their descent, Pathfinder requires fuel only to navigate to Mars; the spacecraft aerobrakes into the Martian atmosphere directly from the Earth-Mars transfer trajectory. Other key design differences are the use of airbags, instead of an active three axis stabilized system, to cushion the vehicles impact with the surface, and a deployable lander able to rite itself from any orientation. Besides lower cost, the Pathfinder design additionally offers the potential of landing at sites that offer too many obstacles for conventional iegged landers.

The Entry, Descent, and Landing (EDL) phase of the Mars Pathfinder mission starts four days prior to Pathfinders arrival on the planet. Having already performed the final trajectory correction maneuver (TCM), turned the spacecraft to the desired entry attitude, and fully charged the main battery, commands were then sent to the spacecraft to re-configure it in preparation for EDL. These commands contained EDL algorithm parameters which were determined as a result of ongoing analysis of the spacecraft's current. Opportunities existed to update any of these parameters, or perform a final trajectory correction maneuver (TCM), in the event that the spacecraft's trajectory should change. This was espically germane after entering the Martian gravity well two days prior to atmospheric entry. Once enabled. EDL software begins counting down the time to the first action in the EDL timeline, venting of the Freon from the

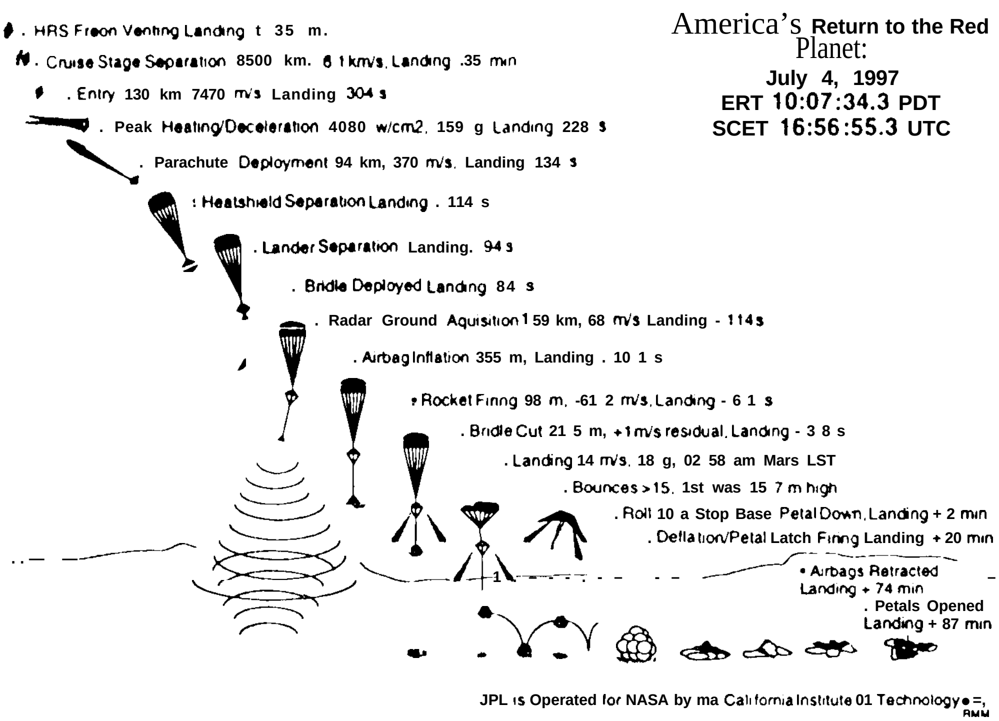

Figure 2. Overview of Mars Pathtinder Entry, Descent and Landing (EDL) performed on July 4,1997

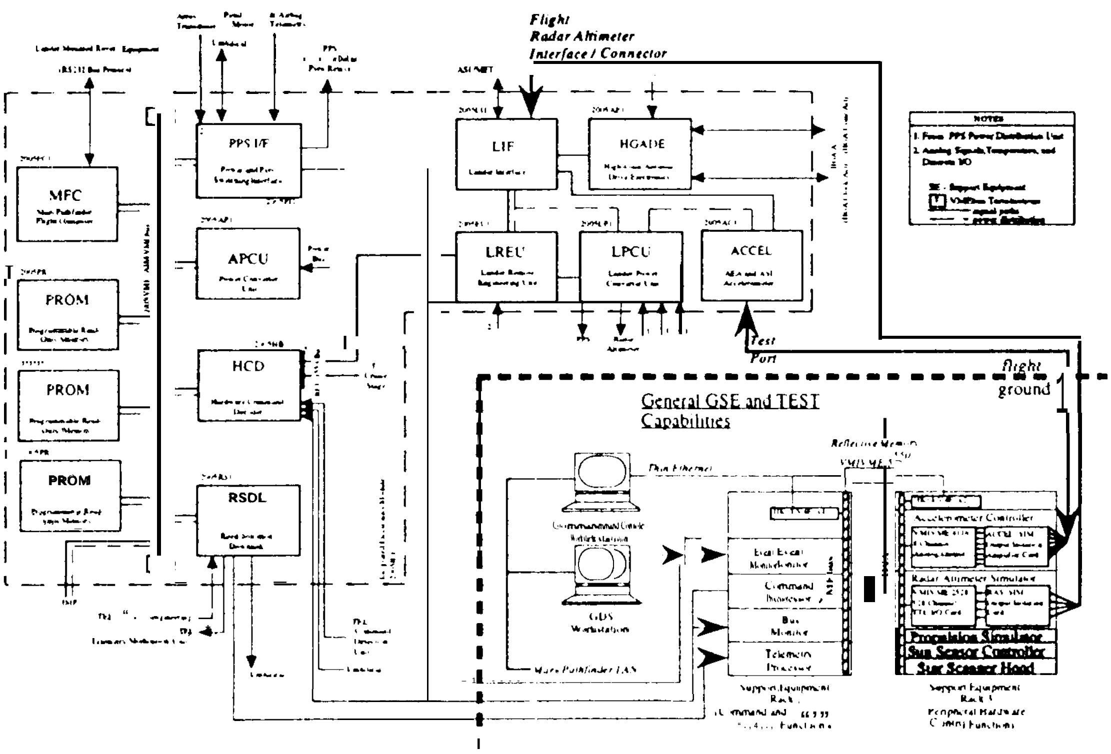

Figure 3. Mars Pathfinder AIM Subsystem Lander Block Diagram / Ground Support Equipment Interface

onboard cooling system. This *event* occurred sixty minutes prior to the commanded Cruise Stage Separation (CSS) time. Sufficient time was allowed between Freon venting and CSS to damp out any nutation or correct for any pointing errors resulting from the vent.

One hour after venting and approximately thirty-five minutes before landing (figure 2), pyrotechnic devices were fired to cut the cables going to the cruise stage and blow the bolts connecting the cruise stage to the entry vehicle. The cruise stage slowly drifted away from the entry vehicle and with it's departure, all commandablity and digital telemetry was lost until the lander had reached the surface and opened it's petals. A small whip antenna was placed on the lander to provide RF subcarrier semaphores on the progress of EDL. However, with the Earth being very low on the Martian horizon, and widely varying lander velocity and orientation, the chances of deciphering these signals in real time were small. Post-process ng of the recorded data might provide information on actual EDL actions in the event that spacecraft telemetry was not received after landing. From this point on, EDL became fully autonomous and all actions were performed as a result of acceleration and altitude measurements. In the event that the data collection hardware did not function properly, backup action execution times had been established. Critical event times were loaded into hardware registers to protect against a reboot of the computer.

Fifteen minutes after Cruise Stage Separation at an altitude of over 4000 km, flight software started collecting and recording measurement samples at a high rate for later play back. Recorded data included measurements of vehicle accelerations, temperatures, pressure, and altitude, in addition to engineering status telemetry. Five minutes prior to landing, the spacecraft entered the Martian atmosphere (defined as the point -130 km above the surface) traveling at 7500 m/s. The onboard accelerometers were called into action to detect the vehicles deceleration as Pathfinder passed through the atmosphere. The forces on the lander were expected m approach 20 g's at the point of peak deceleration. By utilizing the vehicles measured accelerations. software was able to determine the proper instant at which to fire the mortar [o deploy the parachute. For the parachute to deploy properly. the vehicle must be traveling more than Mach 1.2 and the dynamic pressure should be less than 660 N/m^2.

Approximately twenty seconds after the parachute had been deployed, the heatshield retainer bolts were blown. After ten seconds had passed to allow the heatshield to fall away, the lander was released down a 20 m bridle. In this configuration, the radar altimeter started looking for a valid ground return. Once software received data measurements of the vehicles changing height, it was able to determine the correct instant to inflate the airbags, fire the retro rockets, and finally cut the bridle releasing the lander on it's 15 M freefall to the Martian surface.

As the airbag cushioned lander was bouncing around on the Martian surface, accelerometer data was once again utilized to determine when the lander had stopped rolling, and in what orientation the lander had come to rest. When the software had determined which petal was most up, the hour long airbag deflation and retraction process began. Accelerometer data was continuously examined throughout the retraction and deployment process to search for any orientation changes. Once the airbags were fully retracted, the lander started to open it's petals and reveal it's content. From the first autonomous event in EDL to full completion, just over three hours had passed. The lander was now waiting for the Sun to rise on it's new home *so* it could start sending data back to Earth telling about it's bumpy ride and it's new surroundings.

AIM SUBSYSTEM

The Mars Pathfinder Attitude and Information Management (AIM) subsystem combines the traditional areas of attitude control with command and data handling. AIM manages and controls the flight system during all phases of the mission. That encompasses all software and hardware that addresses such spacecraft functions as:

- Interface with and control of the Telecom, Power & Pyre, Thermal, Propulsion. and Science subsystems.
- Processing of all command and telemetry data streams,
- Spacecraft mode configuration management
- Attitude determination, control. and trajectory correction maneuvers.
- Autonomous data processing and control of entry descent and landing actions.

- Spacecraft fault protection and recovery.
- Collection and processing of all science data
- Control of the lander-rover communications link.

The sole processor on the spacecraft, the Mars Pathfinder Flight Computer (MFC), was designed around a 32 bit IBM RAD-6000-SC processor with 128 M-bytes of ram running at 20 MHz. The operating system running on the MFC is VxWorks®, and all flight code is programmed in C. The MFC resides on a hard VMEbus backplane with limited modifications. Power for the bus is provided by the AIM Power Converter Unit (APCU). Three Electronically Erasable Programmable Read Only Memory (EEPROM) cards offer 6 M-bytes of storage space for versions of flight code and critical data storage including EDL measurements. Connection with the Telecom subsystem is provided by two cards. The Reed-Solomon Downlink (RSDL) card provides the interface with the downlink side of the radio subsystem, while the Hardware Command Detector (HCD) interfaces with the uplink hardware. Additional logic on the HCD controls a 1553 bus that links AIM's VMEbus hardware with it's peripheral hardware. The Power and Pyro Switching Interface (PPSIF) card provides drive signals which throw latching relays and fire pyrotechnic devices in the power and pyro area. The final resident on the backplane is the buffer board of the Imager for Mars Pathfinder (IMP). The high throughput rates required of this instrument necessitated it's placement into the engineering backplane. The remote terminals on the 1553 bus were two Remote Engineering Units (REU). One card supported the cruise stage peripheral hardware while the other interfaced wit the landed components. These cards provided peripheral command decoding and data collection of both analog and digital signals.

The Pathfinder Accelerometer (ACCEL) hardware contains six heads. three designated for science data gathering (ASI), and three for engineering purposes (AEA). The engineering heads are aligned along the -Z, +XY, and -XY spacecraft axis, and are backed up by science heads aligned along the X. Y. and Z of the spacecraft. Each of the heads can independently measure acceleration in three different ranges. ± 16 mg, ± 800 mg, ± 40g. The ranges are flight software commandable. While the engineering heads are commanded to the ± 40g range early on in the EDL timeline. flight software performs autonomous range switches on the science heads. This functionality was added in order to obtain data on the outer reaches of the Martian atmosphere. By comparing the measurements received from the engineering and science heads, data samples were validated before being fed to EDL algorithms. The accelerometer data output to the Lander Interface (LIF) unit is in the form of sixteen bit digital words representing the measured acceleration. Data is collected from the accelerometers at a rate of 32 Hz. per head.

The radar altimeter selected for the Pathfinder mission was an off the shelf space qualified unit built by the Honeywell Corporation. The altimeter determines the lander's height above the surface by measuring the time required for an RF pulse to travel from the transmitting antenna to the terrain and back to the receiving antenna. The altimeter can measured from O to 5000 ft at a rate of 50 samples per second. Data output returned to the LIF is in the form of a 16 bit digital word representing the absolute altitude.

With the exception of the additional accelerometer heads, there is no redundancy in any of the hardware required to properly perform EDL.

TESTING OVERVIEW

While Pathfinder was defined as a class C mission, project management decreed early on that the testing process would be worthy of a class A program. The project motto used during development was build it well, build it quick, and then test, test , test. This was especially evident for components of EDL. While hardware utilized for EDL came with some heritage and required a minimal amount of development (with the exception of the airbags), extensive testing was still required to verify that the mission specific design modifications could properly meet all imposed requirements.

While it was impossible to perform an end-to-end test of the hardware and software involved in EDL. extensive testing was performed on individual components of the system. Experts in their respected fields were utilized to properly validate Pathfinders EDL subsystem. This included:

- Aeroshell ablative material arc jet tests performed at the Ames Research Center.

- Entry dynamics simulation performed at the Langley Research Center.
- Parachute and mortar tests were performed in Boise, Idaho.
- Bridle deploy testing was performed at the China Lake Naval Weapons Research Center.
- RAD rockets testing was performed at the China Lake Naval Weapons Research Center.
- Radar Altimeter testing was performed by Honeywell Corporation.
- Airbag inflation and drop tests were performed at the Sandia National Laboratory and the NASA Lewis Plum Brook Station Chamber
- Airbag retraction and petal deployment testing was performed at JPL.
- EDL algorithms were tested standalone using software simulations at the Langley Research Center and JPL.

EDL TESTING IN PATHFINDER'S FLIGHT SYSTEM TESTBED

Verification of the interactions between flight software, EDL algorithms, and flight hardware was performed in the Mars Pathfinder Flight System Testbed (FST/P). The FST/P was used to initially test and verify all flight hardware prior to it's delivery to spacecraft assembly, and still contains engineering model hardware and flight software that is identical in fit , form and function to that on Mars. The lab also contains ground support equipment that could stimulate or simulate peripheral hardware for testing of all phases of the Pathfinder mission; launch, cruise, entry, descent, landing, and surface operations. The main functions of the FST/P in EDL testing was to verify the end-to-end data flow of measurement collection, software processing, and EDL event execution. This was accomplished by stimulating the accelerometer hardware and simulating altimeter data.

The accelerometer hardware contained a test port that would allow stimulation of each of the six heads using current bias signals. The input bias was produced from a 16-bit commercial analog output card, and buffered by custom interface logic.

The radar altimeter selected for the Pathfinder mission did not offer a test port to allow stimulation of the flight hardware. Ground Support Equipment (GSE) was designed to simulate the interface between the radar altimeter and the Lander Interface (L IF) card. As such, the GSE sent 16 bit digital data words directly into the L(F. For the majority of EDL testing performed in the FST/P, the altimeter was removed from the configuration and replaced with this ground simulation hardware.

Two separate racks of hardware made up the test set employed in the Pathfinder testbed. The first rack housed all command and telemetry functions while the second included all peripheral hardware control functions, including those related to the Accelerometer and Radar Altimeter. All of the ground support equipment electronics resided in commercial VMEbus' running C code in a VxWorks® operating system. The code executed on Heurikon V4F single board computers residing in these backplanes. The software was downloaded onto these cards using a thin ethernet line connected to a local port of a SUN® workstation. Key to the EDL test program was the ability to monitor time broadcasts sent on the 1553 bus. This information was used to synchronize the spacecraft and support equipment clocks.

NASA's Langley research center performed extensive analysis and modeling of Pathfinder's aerodynamic descent through the Martian atmosphere. The outputs of these runs were data files containing time tags and the corresponding accelerations and altitudes. These runs also determined the desired spacecraft reactions to the particular test case. Ground software utilized these files to bias the flight accelerometer and radar altimeter accordingly. Measurements could then be made of the time offsets between desired actions and flight software's actual actions. All software actions were either in the form of drive signals sent to the power & pyro subsystem via the PPSIF card or in the form of subcarrier semaphores sent to the downlink hardware via the RSDL card. Monitoring of these signals was provided by ground support equipment. which outputs a description of the specific action in addition to the event timetag. Analysis of the offset between "optimal"' and actual event times formed the basis of the EDL electronics / software verification effort.

Three main test cases were developed test EDL. The nominal test case simulated the spacecraft entering the atmosphere at the desired angle of attack. The undershoot test case simulated a worse case decreased entry angle while the overshoot tested out the worse case limit of a greater than nominal angle of attack. Reset recovery test cases were performed by power cycling the system in the midst of these test runs, while fault protection and hardware / software robustness test were done by hand modifying the data input files. By performing multiple runs on these cases, and executing extensive robustness tests, we were able to thoroughly validate the EDL end-to-end software and hardware system.

SANDBOX TESTING

One of the areas that Pathfinder excelled in testing was in it's Operational Readiness Test (ORT) program. The project made every effort to perform as many tests in a flight-like configuration as possible. While the clean room portion of the FST/P provided an environment to test all phases of EDL, the sandbox portion of the testbed offered an environment for performing realistic retraction and deployment tests.

A full scale model of the Pathfinder lander was placed in a room 10 m by 20 m in size. Fully functional airbags, retraction motors, petal actuators, accelerometers, high gain antenna, and flight imager were mated to this lander. The room also contained sand and rocks for simulating a variety of Martian environments, especially useful to tax the rover operators and drivers. This allowed for extensive and realistic testing of the landed and surface portions of the Pathfinder mission.

Operational tests for EDL usually commenced at Martian entry minus five days with the turn to entry attitude. Simulated navigation data was then sent to the navigators so they could practice their ability to not only determine if key EDL parameters required updating, but if a contingency TCM was required to obtain the desired landing location. Similar to July 4, digital data flow was ceased when the cruise stage would have been jettisoned, and engineers had to analyze the data when it was sent to the ground at a later time (similar to events on landing day).

This environment proved extremely valuable in preparing for Mars. Numerous problems with ground tools. telemetry visibility. and flight software were discovered while performing readiness tests. All of the problems were addressed, resolved. and re-tested in the FST/P before the new software was sent to the spacecraft.

RESULTS AND CONCLUSIONS

The culmination of all the hard work and long hours came on July 4, 1997 when Pathfinder descended to the Martian surface. While EDL has always been thought of as the riskiest part of the Mars Pathfinder mission, the ease with which actual events occurred on the fourth of July would never have backed this up. Contrary to everyone's thoughts and predicts, when the Cruise Stage and it's antenna separated from the entry vehicle, RF carrier signal was observed throughout the majority of the EDL process. When the signal was observed that indicated EDL had apparently successfully completed, everyone who had ever worked on the Pathfinder project rejoiced. All of the personal sacrifices made for this mission had been rewarded. As wonderful and memorable as these radio blips were, they would pale in comparison to the data about to be returned from Mars.

Hours later, the first low gain antenna occurred, and telemetry received at that time indicated that with the exception of rover communications (which was resolved the following day), everything was nominal on the surface of Mars. Data playback of the ride to the surface revealed a much more favorable descent than ever expected, and the first images of the surface revealed an incredible Martian landscape.

Figure 4 shows the intense heat the heatshield was subjected to as the entry vehicle plunged through the atmosphere. The location of this temperature sensor was on the shoulder of the aeroshell at a depth of 9.5 mm from the surface. Unfortunately, the sensor that was located at the aeroshell stagnation point at a depth of only 4 mm never delivered valid data measurements.

Figure 5 shows the magnitude of the measured acceleration the spacecraft experienced on it's descent to the red planet. Key events such as atmospheric entry. parachute mortar firing, parachute deployment. retro rocket firing. and bounces on the Martian surface are evident in the data.

Figure 6 shows the data returned from the radar altimeter as the lander approached the surface. Measured rate of descent was approximately -6 I meters / second, well within design limits. The tiring of the retro rockets is also evident near the end of the data as the lander rate of descent decreased to almost zero.

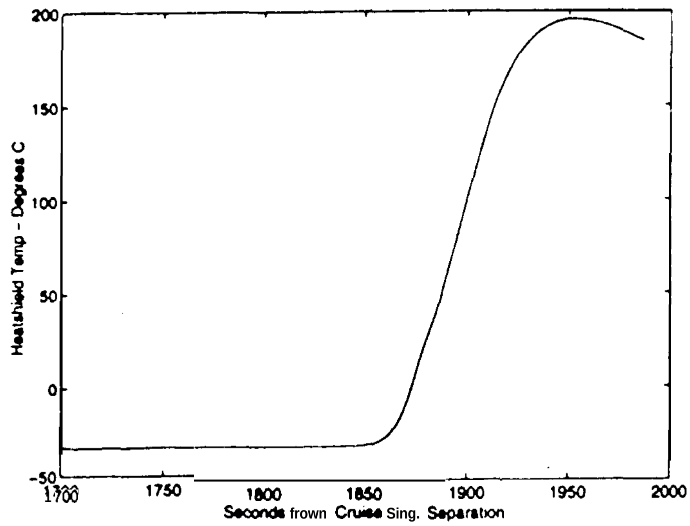

Figure 4. Descent Temperatures

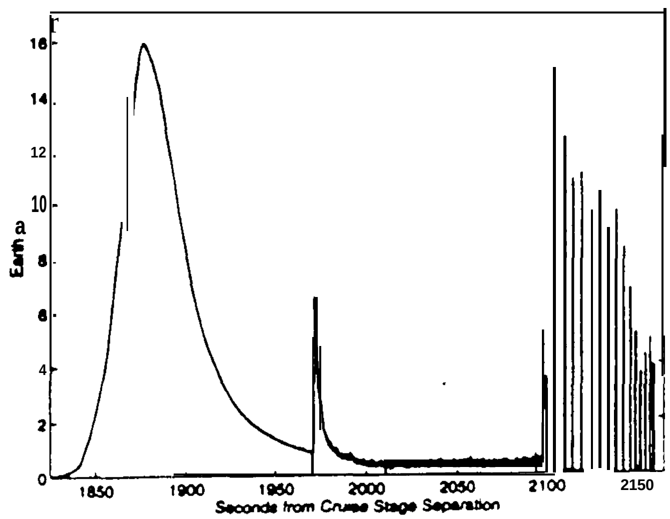

Figure S. Descent Accelerations

The Pathfinder lander and Sojourner rover have met and exceeded all requirements and expectations assigned them. To this date, the lander and rover have survived for over 75 Sols on the surface of Mars. Over 16,500 images have been returned [o Earth along with over a million meteorological measurements. The rover has traversed over 150 m and performed more than 15 APXS measurements.

Long outlasting their design lives, it is hoped that the data returned from this mission will not only provide exceptional science findings, but also reveal new lessons and practices for designing and operating future Mars landers. All Pathfinder personnel remain optimistic that there is much more excitement still to come from the Pathfinder lander and Sojourner rover.

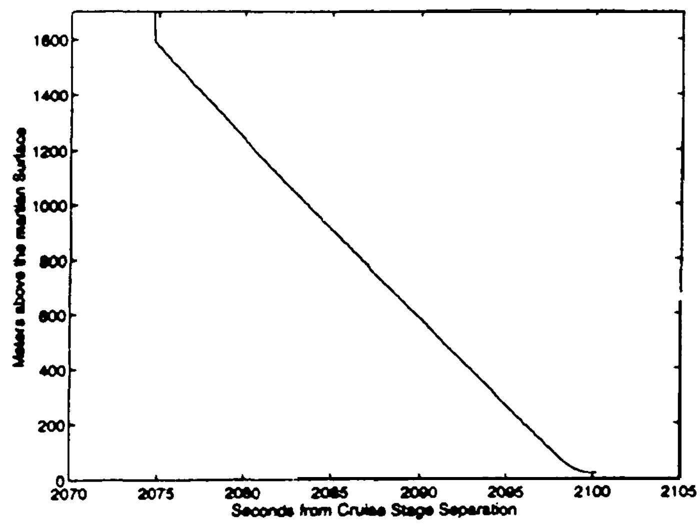

Figure 6. Descent Altitude

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